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ABSTRACT

Highlighting current literature concerning infants' ability to perceive motion, this paper discusses the sensory apparatus that makes motion perception possible. Reviews of the physiology, anatomy, and sensory capabilities of the infant's visual system, as well as a discussion of the neural physiological mechanisms that govern the visual system, are included. The implications of infants' motion perception for their development are discussed. The concluding section reviews several theories of motion perception, and evaluates their efficacy in explaining the infant's perception of movement. Finally, a model of infant motion perception is proposed, and suggestions for future research are offered.
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INFANTS' PERCEPTION OF VISUAL MOVEMENT:
A REVIEW AND THEORETICAL ANALYSIS

by

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I. Introduction

Boring (1942) attributed Purkinje's (1825) work in illusory movement as providing the impetus for contemporary interests in motion perception. However, these interests were largely confined to the adult subject. It was not until nearly 125 years later that psychologists began studying the human infant's perception of motion. The absence of research with infants on this topic was probably not due to a lack of interest, as much as to the difficulties encountered in working with infants. As Haith (1978) has pointed out, infants frequently make poor subjects, primarily because discriminative response indicators are limited (such as the ability to talk), and direct neural anatomical investigations are impossible.

Much of present day interest in infants' visual behavior can be attributed to the early work of Fantz (e.g., 1958) and Berlyne (1958). By providing a reliable method for studying early visual selectivity, these authors opened up new avenues of research that had previously been unexplored. Because infant research plays an important role in providing a better understanding of adult perceptual functioning, as well as contributing toward better delineating the general course of human development, contemporary infant psychology owes much to these investigators.

Following the early work of Fantz and Berlyne, interest in examining infant perception, especially visual perception, blossomed. A cursory review of the literature reveals that this interest has yet to abate. However, most investigators working in the area of visual perception have ignored the infant's perception of movement. In some ways,

the infant perception literature is almost paradoxical with respect to motion perception, as in numerous studies investigators have both employed and are dependent upon the infant's perception of motion. Yet, few studies have involved a specific examination of this ability. Thus, while we know very little about motion perception relative to other visual behaviors, many infant researchers have taken this ability for granted.

The purpose of this review is to describe what we do know about the infant's ability to perceive motion. We will begin by discussing the sensory apparatus that makes it possible for the young organism to perceive motion. Reviews of the physiology, anatomy, and sensory capabilities of the infant's visual system, as well as a discussion of neural "units" sensitive to motion information will be included.

Following the above discussion, the succeeding section will deal primarily with reviewing the work of those investigators that have specifically examined the infant's ability to perceive motion, and will attempt to draw some conclusions concerning the nature of these abilities. This will be followed by a discussion of the possible implications these abilities have for the infant's development, and will focus primarily on those aspects of development that are dependent upon the ability to perceive motion.

The concluding section will contain a review of several theories of movement perception, and evaluate their efficacy in explaining the infant's perception of movement. Finally, a model of infant motion perception will be proposed, and suggestions for future research will be offered.

II. Physiology and Physiological Mechanisms

1. Physiology and Anatomy involved in Motion Perception

The importance of movement perception relative to other visual functions can be demonstrated in two rather indirect fashions. First, when brain injuries to adults cause temporary loss of all visual functions, movement perception is often the first to recover (Riddoch, 1917). Second, motion perception appears to have received special treatment during evolution in the physiology of visually immature animals. In the cerebral cortex of newborn mammals, for example, many visual functions need environmental stimulation to develop, but sensitivity to the direction of visual movement is present from the outset (i.e., little priming is needed--Blakemore, 1974; Barlow & Pettigrew, 1971). Accordingly, Sekuler (1978) claims that during evolution, motion perception was shaped by selective pressures stronger than other aspects of vision. For example, responding to a rapidly moving object may be more important than knowing exactly what has moved. As a result, our visual system is highly developed at birth, and contains neural mechanisms that are specific to motion detection.

The largest proportion of sensory neurons in the CNS is in the visual system, which contains approximately 540 million neurons (vs. 100 million in the auditory system--Sinsheimer, 1971). Furthermore, the complex structure of the eye differentiates and develops earliest in ontogeny. With respect to specific structures of the eye, the pupillary reflex, though sluggish, is present and adaptable to the level of light intensity in both full-term and pre-term infants (Beasley, 1933;

Genzmer, 1882; Guernsey, 1929; Kroner, 1881; Kussmaul, 1859; Sherman et al., 1936; Haith, 1969). With respect to the lens, it has been reported that the newborn can obtain at least a focused retinal image for stimuli presented at one particular distance. The minimal separable angle at this distance is estimated to be between 7.5 minutes to 40 minutes based on the optokinetic response and visual orienting (Dayton et al., 1964a; Fantz et al., 1962; Gorman et al., 1957). This corresponds to visual acuity of 20/150 to 20/800 Snellen, or discrimination of a line separation of 1/60th in to 1/2 in at a distance of 7-1/2 in. Thus, although it was believed that stimuli placed closer or farther away from this distance became increasingly defocused as the distance from the ideal focal plane increased, it is incorrect to think that stimuli placed successively farther in front of or behind this plane simply vanish for the newborn (Haith, 1978).

There is some question as to how functional the retina is at birth. At the simplest level, the rods and cones are differentiated and the outer segments are discernable (Duke-Elder & Cook, 1963; Man, 1964). The shape of the newborn's rods is similar to that of the adults's, whereas the cones are stubbier. It has been speculated that the macula is non-functional at birth (Zetterstrom, 1951, 1955), resulting in a lack of central (foveal) vision, i.e., there are no deep foveal depressions densely packed with 3 to 4 layers of long slender cones. Instead, there is a shallow depression of ganglion cells, bipolar cells, and one layer of short, stout cones. This has led authors such as Bronson (1974) and Karmel and Maisel (1975) to assume that the newborn's visual system is immature or limited. However, Lewis, Maurer, and Kay (1978) recently found that newborns could detect a line 8 minutes wide in the

central visual field. Peripherally, they were able to detect lines 33 minutes at 10 and 20 degrees and 1 minute, 6 seconds at 30 degrees. These results contradict those of Dayton, Jones, Aiu, Rouson, Steele, and Rose (1964), who found that infants can detect lines presented to their central visual field only between 20 and 55 minutes. Although the two studies differed in design (e.g., the detection of a single line vs a grating), the results of Lewis et al. (1978) are intriguing because it may be that the central field of vision is more developed at birth than previously thought.

Although there is not abundant research examining the visual pathways of infants, there is reason to believe that the anatomical and physiological components of the visual system necessary for activity of at least simple cells in the visual cortex (e.g., rods and cones, the lateral geniculate body, cells in layer IV of the visual cortex) are functionally adequate at some level in the normal newborn (Haith, 1978). And, finally, deShonen, McKenzie, Maury, and Bresson (1978) have shown that the infant's effective visual field (i.e., foveal and peripheral vision combined) greatly expands between two and four months. The extent to which near peripheral targets were detected at greater angles of eccentricity than those more distant was modified both by age and the distance from central fixation. Most of this change took place after 3 months.

2. Motion Detectors: Direction-specific

A number of investigators have proposed that much of visual motion perception is governed by underlying physiological mechanisms, or neural motion detectors (e.g., Sekuler, 1975, 1978). The extent to which all

forms of visual movement can be explained by these neural units is an empirical question, and it is not the goal of this paper to resolve the issue. However, it is important to describe what we know about these structures, especially as they relate to the data on the infant's perception of visual movement.

Evidence for the neural detection of motion comes primarily from two sources. The first are those psychophysical experiments conducted with human adults that attempt to delineate neural structures indirectly through psychological data. A second source comes from the physiological and histological experiments on non-human organisms (e.g., monkeys, cats, and frogs). Because neither source has used the human infant as its subject, the extent to which these data apply to this population rests on the assumption that valid inferences can nevertheless be drawn from the adult and comparative literature.

Much of the psychophysical evidence for motion detectors relies on electronically generated stimuli, such as gratings. Gratings are generally patterns of alternating parallel light and dark bars, that can be made to drift across the face of a cathode ray tube display at any desired rate and direction. The visual impact of a moving grating depends upon the spatial frequency and its rate of movement (i.e., temporal frequency or velocity). Based on adult research using such stimuli, it has been suggested that the visual system contains mechanisms sensitive to changes in direction. In psychophysical terms, the prolonged exposure to a grating moving in one direction should elevate the threshold for an object moving in the same direction as for one moving in the opposite direction (Sekuler & Ganz, 1963). Pantle and Sekuler (1969) found that a fixed direction of adapting motion

produced more elevations of threshold for a same-directional than for an opposite-directional test grating. This direction-specific adaptation has been demonstrated numerous times psychophysically (Sekuler et al., 1968; Tolhurst, 1973; Sharpe & Tolhurst, 1973; Levinson & Sekuler, 1974), as well as electrophysiologically (Clarke, 1974).

The existence of direction-specific mechanisms does not imply that the detection of moving stimuli is mediated by independent direction-specific detectors. In order to demonstrate the existence of independent detectors, one must measure the summation between stimuli moving in opposite directions. If there are independent detectors, and if each detector has virtually no sensitivity to movement opposite its preferred direction, then thresholds for a grating moving in one direction should be unaffected by the presence of a contrast moving in the opposite direction. There is both psychophysical (e.g., Levinson & Sekuler, 1973, 1975) and physiological (e.g., Cooper & Robson, 1968) evidence to suggest that there are independent detectors. For example, Cooper and Robson (1968) measured the responses of directionally selective and non-directionally selective neurons to moving or counterphase gratings. They found that non-direction-specific cells responded as well to a counterphase stimulus as to a drifting grating of equal contrast. However, direction-selective neurons responded less than half as well to the counterphase grating. This evidence is similar to the psychophysical findings.

3. Motion Detectors: Velocity

In addition to direction-sensitive detectors, structures capable of coding velocity information are also thought to exist (Sekuler, Pantle,

& Levinson, 1978). The simplest code for velocity would be one in which the output of a single-movement sensitive cell is increased as stimulus velocity is increased. This additive model would predict that high impulse rates would be associated with fast moving stimuli and low rates with slow moving stimuli. Subjective speed would be determined by the absolute level of output of movement-sensitive cells.

The additive model has been shown to be true for the frog (Grusser & Grusser-Konehls, 1973), but the directionally selective cells in the rabbit (Barlow et al., 1964) and the cat (Hubel & Wiesel, 1965; Pettigrew et al., 1968; Ganz & Lange, 1973; Movshon, 1974) respond to a relatively narrow range of velocities. The responses are greatest at intermediate velocities and less so at both slower and faster velocities. Moreover, the optimal velocity for stimulating a cell varies from one cell to the next. Thus, it may be possible that perceived velocity depends on the relative activities among velocity-tuned cells. This substitutive model is consistent with the psychophysical evidence. For example, Pantle and Sekuler (1968b) found that the amount of direction-specific adaptation produced by a moving grating depends on how close the speed of the adapting stimulus is to the speed of the test stimulus. Direction-specific adaptation was greatest when the speeds of the adapting and test stimuli were similar. The conclusion reached by Sekuler and Pantle (1968b) was that the human visual system does contain different velocity-tuned mechanisms which can be selectively adapted to a limited range of stimulus velocities.

4. Motion Detectors: Anatomy and Physiology

If we accept the fact that the human visual system contains mechanisms sensitive to changes in both direction and velocity, it is important to specify their location. The retina is the most likely location, since we know that different parts of the retina vary in their response to temporal or spatial stimulation. Brown (1972) claims that the peripheral retina is specialized for motion perception. Brown found that foveal acuity for a moving target declined linearly with angular velocity. In contrast, parafoveal acuity for a slowly moving target was better than for a stationary target. As the velocity increased the acuity degraded.

Lichtenstein (1963) does not support peripheral specialization. Lichtenstein reports that as the eccentricity of viewing increased, the perceived stimulus velocity dropped; furthermore, the apparent drift stopped. As the stimulus velocity increased from .08 to 1.25 degrees/sec, the disappearance of apparent motion required an increasingly greater eccentricity of viewing. Sekuler (1978) interprets these results to imply that the fovea is more sensitive to very slow motion than the periphery. Averting the gaze shifts the target more towards the periphery, or toward an area of reduced motion sensitivity. There is evidence, however, that with higher velocities the relationship between foveal and peripheral motion sensitivity is reversed (e.g., Bhatia, 1975).

There has been some speculation regarding the physiological correlates responsible for the difference between foveal and peripheral sensitivity to motion. For example, it has been found that, (a) the X and Y channels of both the retinogeniculate and geniculostriate pathways differ in their receptive field size, linearity, and conduction velocity

(Enroth-Cugell & Robson, 1966; Hoffman, 1973); (b) the neurons of the two channels respond best over very different stimulus speed ranges (Hofman, 1973); (c) Y cells are faster conducting and have a more pronounced transient response to spatio-temporal modulation; (d) the X channel carries information primarily from the center of vision, whereas the Y channel is responsible for much of the analysis of peripheral stimulation; and (e) Y cells (transient type) vs X cells (sustained type) are more sensitive to stimuli of low spatial frequencies; the Y cells are also relatively less sensitive to stimuli of high spatial frequency. Tolhurst (1973) found that motion sensitive mechanisms in humans, like Y cells, give a far greater response to stimuli of low spatial frequency than do mechanisms sensitive to stationary stimuli.

In summary, foveal and peripheral motion responses differ in the spatial and temporal properties of those moving targets to which they respond best. The periphery shows a distinct preference for targets of low spatial frequency and high rates of temporal modulation or velocity. However, one complication is that any single retinal region contains relatively independent sets of motion detectors, each tuned to different spatio-temporal ranges. A complete parametric elaboration of these regions would be a large and difficult task, and has not yet been carried out.

5. Summary

Several conclusions can be drawn concerning the infant's sensory capacities, as they relate to the perception of motion. We possess neural units sensitive to motion information that have probably been shaped by adaptive pressures during evolution. It appears reasonable to

assume that these units are present at birth, although this research has not specifically examined the human infant and one must hope that the "comparative" literature will generalize to this population. The sophistication of these units coincides with the remarkable visual sensory capacity that also exists at birth. This can be summarized as follows: First, the pupillary reflex seems strong at birth, even in pre-term infants. Second, the infants' accommodative abilities are sufficiently advanced, enabling them to focus to some degree on objects presented within an ideal focal plane. With respect to the retina, the periphery appears better developed at birth than the fovea, although Lewis et al. (1978) has suggested that the fovea is more functional than previously thought. It has also been shown by deShonen et al. (1978) that the effective visual field expands after 3 months, which possibly suggests that the entire retina is adequately developed at birth, but, like the lens, reaches a more mature stature by 3 months. Finally, the remainder of the visual system (e.g., visual pathways, etc.) seems reasonably adept at accommodating whatever information is gathered by the systems mentioned above.

It is difficult to draw any firm conclusions regarding the extent to which motion detectors are functional in young infants. The most conservative position is that these mechanisms are probably not fully functional in newborns. If we assume for the moment that these mechanisms are only limited by the system within which they must work, then it follows that they, like the remainder of the system, do not reach "adult-like" status until approximately 3 months of age (although they may function at a lower level before 3 months). This conclusion rests on the assumptions that: (a) the assumed physiological and

anatomical correlates of motion detectors are as developed at birth as the rest of the visual system, which does not reach maturity until at least 3 to 4 months of age, and (b) little priming is needed to activate these units. At the present time there is little evidence that directly addresses these issues, and it remains to be seen what future research reveals.

It should be apparent from the above that the infant's visual sensory capacity is relatively advanced at birth, and should thus provide the infant with the ability to perceive movement from an early age. The next section, then, contains a review of those studies that have specifically examined this ability. This section will include a discussion of how the visual system operates in visual pursuit, and studies will be reviewed that have examined visual tracking, and preferences for moving vs stationary stimuli. We will also discuss some of the parametric variables that affect motion perception. Following this discussion we will consider what implications these abilities have for other aspects of infant development.

III. Direct Evidence for Motion Perception

1. Tracking Studies

There are natural limits of the visual system in tracking a moving object. At least for adults, smooth tracking movements of the eyes appear 0.15 to 0.17 sec after the appearance of a moving object enters the field of vision. The velocity of these movements synchronizes immediately with the velocity of displacement of the target. The minimum velocity of movements of a visual stimulus that will evoke a tracking

movement is 5 degrees of arc/sec, which is approximately the same as the threshold for the perception of movement (Yarbus, 1967). With an increase in the velocity of the object followed, the eyes lag behind by a gradually increasing amount. At the same time, the velocity of movement of the image over the retina increases and this increase is the reason visual acuity fails. More specifically, visual acuity declines with an increase in velocity of movement of the tracked stimulus over 60 to 70 degrees/sec, resulting in the appearance of saccadic eye movements (Reading, 1972). Smooth tracking movements of the eyes occur only if the moving stimulus is in the field of vision. Analysis of the microstructure of tracking eye movements shows that these movements repeat the trajectory of the stimulus followed, changing their direction and velocity without any corrective saccades (Shakhonovich, 1977).

Considering the limits of the visual system, then, what do we know about the infant's ability to track moving objects? It has been known for some time that neonates will "lock onto" a moving stimulus and track it (Barten, Birns, & Ronch, 1971; Brazelton, School, & Robey, 1966; Dayton & Jones, 1964; Dayton et al., 1964; Dayton, Jones, Steele, & Rose, 1964; Tronick & Clanton, 1971). Wolff (1959) found that infants 24 hours old will make visual pursuit movements during periods of alert inactivity. He noted that infants were able to follow a stimulus with their eyes and head in both vertical and horizontal directions, as well as in circles. Other investigators have found that when the stimulus is a series of vertical stripes, and motion is present over the entire visual field, the neonate's response consists of smooth tracking movements alternating with brief saccadic returns (optic nystagmus--Brazelton et al., 1966; Dayton et al., 1964). When an isolated object is

moved over a stable visual field, neonate pursuit consists of a series of jerky "catch up" movements (Barten et al., 1971; Dayton & Jones, 1964; Dayton, Jones, Steele, & Rose, 1964; White et al., 1964). Moreover, to capture the infant's attention, objects should be introduced to the periphery (Gesell, Ilg, & Bulbs, 1949; White et al., 1964), and the infant's gaze may drift away if the motion is stopped when the object is located within the foveal area (White et al., 1964).

In an attempt to examine different aspects of visual pursuit, Wolff and White (1965) looked at the relationship between state, pacifier sucking, and visual pursuit. The authors reported several interesting findings. First, pacifier sucking was generally found to inhibit head rotation and consequently reduce the range of overall pursuit movements. Second, infants conjugate eye movements were more persistent when the infant was alert and inactive vs. waking and inactive. Third, infants pursue with their eyes as well as or better while sucking on a pacifier than during alert inactivity, and consistently better than during waking activity. Finally, infants pursue a moving object with their eyes more consistently right after they begin to suck on a pacifier than after sucking for several minutes.

Although Wolff (1959), Wolff and White (1965), and others have demonstrated the capacity in newborns to follow a continuous moving object, Wickelgren (1969) asked if newborns could respond ocularly to visual movement represented by a change in visual position, and what effects the rate of change would have on pursuit. In the first experiment, infants were presented with a stationary light centered in front of the infant's eyes, a blinking center light, and a repeating series of three horizontal lights (e.g., right, center, left, center, etc.).

Blinking and non-blinking intervals were 1/2 sec, respectively. Infants in a second experiment received the same repeating series of horizontal lights as in Experiment 1, but at three different light durations (1/2-, 1-, and 2-sec). In both experiments, all subjects responded appropriately to the moving lights by shifting their direction of gaze predominately to the left when the left light was on, and to the right when the right light was on. The infants in both experiments were unable to consistently follow the lights between the regions, and could not look directly at the lights in any stimulus condition (i.e., there was no evidence of ocular convergence). Furthermore, there was no evidence of improved ocular following between regions during exposure to any moving light sequence (i.e., increased light duration failed to increase the precision of shift responses).

The neonate's inability to converge both eyes on one place may have contributed to the failure of infants to follow the lights between regions. If such organized tracking responses are in part dependent on ocular convergence, then such responses should be present in older infants.

In an attempt to assess organized tracking responses in 20-day-old infants, Nelson (1968) gave subjects repetitions of an uninterrupted sequence of a left-to-right row of six flashing lights. When the infant was observed to be tracking the lights, the sequence was interrupted by preventing two adjacent lights from flashing. Nelson (1968) reported that all subjects showed a strong initial organization of tracking responses such that once the infant had looked at one light, the offset of this light in conjunction with the onset of the light to the immediate right triggered an eye movement to the new light. At first

these organized tracking movements occurred primarily to the right of both the infant's midline and the center of the pannel. However, after relatively few sequences the tracking behavior began to include the left-most lights. Overall, right ocular movements accounted for 93% of all lateral ocular responses to light offset preceding interruptions. In contrast, left eye movement responses accounted for 53% of all left ocular responses after the offset of the sixth light.

Nelson (1968) claims that the differential response of subjects to the offset of the sixth light relative to the offset of lights before interruption can be accounted for by a centrally stored schema or analogue of the overt response sequence. This schema would allow the continuation of an overt sequence of right movements after the offset of a light followed by an interruption despite the absence of two lights typically present in the stimulus cycle.

In a later study, Nelson (1971) observed 5- and 8-month-old infants as they watched a model train locomotive travel an uncovered track circuit, briefly disappear at one end of a tunnel, and reappear at the tunnel's opposite end to begin a new lap. After subjects successfully completed four of eight trials in which they watched the train disappear and then made a visual movement to the opposite end of the tunnel, the infants received subsequent trials where the train reversed direction in the tunnel and exited through the end it initially entered. Two sets of reversal trials were included. Across subsequent trials, the infants looked progressively closer to the tunnel exit before the train's reappearance, made more visual anticipations of reappearances, and required shorter delays in spotting the train after its reappearances. These results were interpreted to be in accord with Piaget's (1952, 1954) ob-

servations. Like Piaget, infants in Nelson's study followed a general rule: Look for the reappearance of an object which moves and disappears along the extension of its trajectory. Nelson (1971) thus concluded that infants "possess both the capacity for and the proclivity to short-term accommodation of action patterns to the details of encountered patterns of object movement" (p.194).

A number of investigators have attempted to explore some of the physical parameters governing infant tracking behavior. Harris, Cassel, and Bamborough (1974) assessed the degree to which tracking activities were supported by the displacement of an object relative to a background, in contrast to displacement of a whole field. In the first experiment, 10- and 16-week-old infants saw either an object moving against a stationary background or the object and background moving together at the same speed. For both groups tracking was impaired when the object did not move in relation to the background. In a second experiment, three groups of infants (14-, 21-, and 27-weeks) each experienced the same conditions as in Experiment 1, as well as a condition in which the object and the screen moved at the same speed in opposite directions. As in the first experiment, tracking was supported by the displacement of an object relative to the background, whether or not the background was stationary or moving. Relative displacement served to maintain tracking, rather than to elicit capture. In both experiments there were no age effects, although there was some evidence that the younger subjects might be more sensitive to the difference between the stationary-background, and background-and-object-together condition.

The authors interpreted these findings to suggest that the absence of relative motion abbreviated the pursuit of a moving object but did

not reduce the probability of capture. That is, when a subject engages in smooth and accurate pursuit, the absolute motion cues for the target (resulting from motion relative to the retina) are reduced. Hence, relative motion cues may be required for sustained tracking. This may explain the lack of smooth central pursuit some authors have found in newborns (e.g., Dayton et al., 1964; White et al., 1964). It may be that sustained pursuit requires a sensitivity to relative motion and that previous investigators failed to provide relative motion cues. It may also be that the newborn is in fact sensitive to both absolute and relative motion cues, but is unable to achieve the integration required for smooth pursuit.

A second variable thought to contribute to visual pursuit is the rate of stimulus movement. Volkman and Dobson (1976) investigated the responses of 1-, 2-, and 3-month-old infants to different rates of oscillatory motion. Infants were presented with two rear-projected, simultaneous displays of identical checkerboards, one of which was stationary while the other moved. The moving stimulus varied in eight steps, between 3.5 and 120 cycles per minute (CPM). In the control trials, neither stimulus moved. Observers were "blind" to condition, and rated each trial (18 per session) on three dimensions: (a) the stimulus on which the first fixation occurred, (b) where the infant was judged to be looking (left, right, or neither) at the end of a 5-sec interval during a trial, and (c) a report at the end of the trial indicating which stimulus was judged to be the moving one. In general, the authors reported that at least by 1 month, infants behave differently when presented with moving and stationary stimuli, and that this differential behavior can provide reliable cues for an observer to

judge which is the moving stimulus. These cues were more discernable as the rate of movement increased up to 90 CPM, and then they became less discernable. Finally, the cues provided by all three age groups led to essentially the same judgements, but the cues provided by 3-month-olds were somewhat stronger than those provided at 1 or 2 months.

Several conclusions can be drawn from the research on visual tracking. First, one implication for studies dealing with neonates is that alert and inactive babies tend to track better than babies in other states. State may also be an important variable with older infants, although this has not been addressed empirically.

Second, a conclusion drawn from the work of Wichelgren (1969) and Nelson (1968, 1971) is that organized tracking responses to intermittent visual movement and phi movement do not occur until 2 to 3 months. By 5 to 8 months infants are able to accomodate action patterns to the details of object movement. The results of all three studies might easily be interpreted by Hebb's (1949) model, that neural organization in the visual cortex results from visual experience mediated by explicit eye movements (Hebb's "cell assemblies" or Nelson's "analogue" or "schema").

By at least 2-1/2 months, infants are sensitive to and may in fact be reliant upon relative motion cues. This has recently received further support from Lasky and Gogel (1978), who found 21- to 23-week-old infants to be very sensitive to such cues. Like figure-ground perception, relative motion cues may be of primary importance to the developing organism. If this is so, Harris et al. (1974) may be correct

in claiming that studies that have failed to find smooth sustained pursuit in newborns may be due to an absence of such cues.

Finally, perhaps the most intriguing finding is that rate of stimulus movement is an important variable in the infant's perception of movement. Sekuler (1978) claims that the fovea is more sensitive to very slow speeds than the periphery but the reverse may be true at higher speeds (Shatla, 1975). If this is correct, the findings of Volkman and Dobson (1976) suggest that by 1 month the fovea is sensitive to speeds of less than 90 CPM, although what happens at speeds greater than 90 CPM is unclear. It may mean that the periphery is not yet sufficiently sensitive to higher speeds, or that the fovea and periphery are not yet able to achieve the integration necessary for tracking rapidly moving objects (indicating a limitation of the visual system in young infants). Volkman and Dobson (1976) pointed out that 3-month-olds were slightly more adept at perceiving speeds greater than 90 CPM. If this is true, this is in accord with the conclusions reached earlier regarding motion detectors; namely, such units may not become fully sensitive until approximately the third month of life, possibly when the periphery becomes more sensitive to increased velocities.

In summary, infants as young as 24 hours are able to track a moving object, although this ability is somewhat limited and is not yet as robust as it is at 3 months. Variables thought to affect visual pursuit include the type of movement (e.g., unidirectional vs. bidirectional), direction of movement (e.g., horizontal vs. vertical), rate of movement (e.g., fast vs. slow), nature of movement (e.g., intermittent vs. continuous), and a variety of experimental arrangements (e.g., stimulus viewing distance, hue, size, etc.). These variables may be orthogonal,

although they more commonly exist in combination, as will become apparent later.

2. Preference Studies

The ability to track a moving object from an early age is merely one way of bringing attention to the importance of motion in the perceptual world of the infant. It is also widely known that infants fixate stationary objects as well. Thus, one way of making even clearer the relative importance of movement vs. static perception is to compare infant preferences for moving vs. stationary stimuli.

Silfen and Ames (1964) investigated age differences in infants' preferences for moving vs. nonmoving stimuli (checkerboards), using a paired comparison procedure (cf. Fantz, 1964). Groups of 7-, 16-, and 24-week-old infants saw simultaneous presentations of a stationary vs. moving target. Different stimulus speeds were incorporated into different trials. The authors reported that 7-week-old infants had no preferences for, and were unable to discriminate, small amounts of movement. In contrast, 16-week-olds showed a peak preference for a fairly slow moving stimulus (a moving belt with an angular speed of 1 degree, 12 minutes per sec) and less preference for faster speeds. Finally, the oldest group showed a steady increase in preference for faster speeds over the entire range used (0 degrees, 13 minutes to 3 degrees, 3 minutes per sec).

Wilcox and Clayton (1968) conducted two experiments examining fixation of 5-month-old infants to a silent, color motion picture of a woman's face. The stimuli varied in amount of movement (moving vs. stationary) and facial expression (smiling, frowning, and neutral). A

strong preference was found in both experiments for moving over stationary stimuli, although there was little evidence that infants differentially fixated different facial expressions. The preference for moving vs. nonmoving faces was consistent with the preferences for moving vs. nonmoving checkerboards used by Silfen and Ames (1964), suggesting that movement may be an important variable in visual preferences regardless of the stimuli used.

Carpenter (1974) explored the effects of stimulus movement on the visual behavior of infants using horizontal movement in which the stimuli were always in the same focal plane. The stimuli were presented to the infants once a week between the time they were 2 to 7 weeks of age. Using the mother's face, a caucasian mannequin head, and a negroid mannequin head as stimuli, each infant was presented with the stimuli in both stationary and moving positions. In the movement condition, the stimulus moved across 8.25 cm in the horizontal plane at a rate of one excursion across and back per 2 seconds.

Carpenter reported that attention increased linearly with age (from 2 to 7 weeks) for both the moving and stationary conditions, and that faces received more attention when moving than when stationary. Interestingly, mannequin faces attracted more attention than the infant's mother's face, but there was no differential attention to the two mannequin faces.

In summary, Silfen and Ames (1964) demonstrated greater attention to vertically moving than to stationary checkerboard patterns at 16 and 24 weeks, but not at 7 weeks. Wilcox and Clayton (1968) found that 20-week-old infants fixated motion pictures of moving faces longer than nonmoving faces and Carpenter (1974) found greater attention to moving

than to stationary three-dimensional faces from as early as 2 weeks.

It should be clear from the foregoing that infants generally prefer moving over nonmoving stimuli, although the variables of type of movement and the nature of the stimulus object may interact with age. At least for animate (e.g., face) stimuli, such preferences may surface as early as 2 weeks.

Although the work of Silfen and Ames (1964), Wilcox and Clayton (1968), and Carpenter (1974) indicate that infants as young as 2 weeks prefer moving over stationary stimuli, what is not clear is how infants respond to and process movement information. It is also uncertain if different types of movement are responded to differently.

Haith (1966) attempted to determine if visual movement would produce a decrement in the newborn's sucking response and whether or not repeated exposures of the same stimulus would result in a decrement of responsiveness. Infants between 24- and 96-hours-old received 24, 10-sec trials (12 experimental, 12 control) of an alternating succession of left-to-right and right-to-left lights. Haith reported that a reduction in sucking was reliably greater during the movement vs. non-movement condition, and that this sucking suppression failed to habituate. These results provide further support that moving objects elicit more attention than stationary objects.

In a later study, Haith, Kessen, and Collins (1969) investigated the impact of three levels of stimulus complexity (type of movement) on limb movements and sucking in 2- to 4-month-olds. The stimulus was a light which changed position 32 times in each of six 24-sec experimental trials. The least complex stimulus made eight steps (four cycles per trial) around the perimeter of the matrix in either a clockwise or

counterclockwise direction. The intermediate level made 16 steps (two cycles per trial) in the same fashion as in the simple level, but was not so constrained to the perimeter of the matrix. The most complex level made 16 steps (two cycles per trial) but moved randomly around the display. At all levels of complexity only adjacent bulbs in the display were sequentially illuminated, and these occurred in either a horizontal or vertical position.

Haith et al. (1969) reported that limb activity was suppressed by the most simple and most complex patterns of visual movement, but was facilitated by the patterns of intermediate complexity. This same non-linear pattern was found between sucking and complexity, but sucking was consistently suppressed by stimulation and the differences were not statistically significant. No systematic habituation of responsiveness was found, whether measured by limb movement or sucking; one exception was a large suppression of sucking to stimulation on the first experimental trial, followed by smaller but virtually equal suppressions on the remaining trials.

Implicit in Haith's research (1966, 1969) is the suggestion that infants up to 4 months of age are so drawn to a moving stimulus to which, unlike their responses to most stationary stimuli, they fail to habituate and continue responding at a high level. Why this attention fails to habituate is not certain. Although it has repeatedly been shown that infants are more attracted to moving than to stationary stimuli, one would only predict that habituation would take longer, not that it would fail to occur. Thus, a more likely explanation is that the number of trials (which were fixed in both experiments) were too few to promote habituation. This interpretation is supported by a recent

study by Gibson, Owsley, and Johnson (1978) using 5-month-olds. Gibson et al. asked if the motions in the stimulus array that are caused by movement of a rigid object (e.g., a solid object with no apparent elasticity) provide information for an invariant property, even though the particular rigid motions differ. The perception of rigid motion was compared with the motion of deformation that specifies elasticity in contrast to rigidity to the adult perceiver (e.g., a sponge being squeezed; Fieandt and Gibson, 1959).

Using an habituation paradigm, Gibson et al. (1978) first presented infants with successive random presentations of three types of rigid motion until an habituation criterion was attained. Following habituation, one-half the infants received a fourth type of rigid motion, while the other half saw a deformation. The authors reported that infants habituated at different rates to different types of motion (i.e., fastest to looming motion, second to rotation around a vertical axis, and slowest to rotation in the frontal plane and around a horizontal axis). Furthermore, subjects dishabituated to the deformation but not to the fourth type of rigid motion, suggesting that infants detected the invariant property of rigidity and differentiated it from the deformation.

Gibson et al.'s findings (1978) suggest that infants (at least by 5 months) do habituate to moving stimuli, although the rate of habituation varies with the type of stimulus movement. What is not clear from any of the research reviewed is how different kinds of moving stimuli (vs. different types of movement) affect habituation.

3. Summary

Several conclusions can be drawn concerning the perception of moving vs. stationary objects. First, infants from the first day of life seem to prefer moving over stationary objects. Moreover, attention to moving objects habituates at a slower rate than to stationary objects; this habituation may be governed by the type of stimulus movement (e.g., simple vs. complex; looming vs. rotation in the frontal plane). In terms of the complexity of movement (different types of movement being more or less complex), it is not clear why rate of habituation covaries with type of movement. Haith et al. (1969) proposed that infants come to expect or anticipate certain transformations and that a violation of these expectations serves to maintain attention. The notion that infants anticipate or set up certain expectancies about events in their world seems reasonable in light of the organized tracking responses Nelson (1968, 1971) observed in infants as young as 80 days. That is, for infants to track a sequence of lights or correctly decide from what end of a tunnel a train will reappear, they must anticipate what will happen next. Furthermore, if a violation of these expectations serves to sustain attention, it may help account for the different rates of habituation Gibson et al. (1978) observed for different types of stimulus movement. Thus, the more complex a type of movement is, and hence less predictable, the more likely it is that the infant will take longer to habituate. And, the younger an infant, the less likely it is that he/she will be able to "process" complex types of information and thus more likely to either fail to habituate or habituate at a slower rate.

With regard to the observed age differences between Silfen and Ames' (1964) and Carpenter's (1974) study, a further consideration is

that the type of stimulus used (e.g., faces vs. checkerboards) may interact with the type of stimulus movement (e.g., looming vs. rotation around the vertical axis), resulting in different levels of relative complexity for infants at different ages. That is, checkerboards and complex movement may result in more overall complexity at one age than faces and complex movement at the same age. Thus, one aspect of future research might be to provide a detailed parametric elaboration of the relationship between type of stimulus and type of stimulus movement.

It should be obvious at this point that there are many variables that contribute to the perception of movement and that these variables usually exist in combination. There is an intuitive "sense" to this, as the stimulus information available to the infant in the "nonlaboratory" world is composed of such combinations; very rarely are the components of the visual array broken down for the infant. Thus, it may be more enlightening to examine the processes that enable the infant to attend selectively to particular aspects of the entire stimulus array than to dissect the array for the infant and examine the perception of isolated segments that may be meaningless to the infant out of context. Such an approach takes for granted the "information pickup" abilities (Gibson, 1966) of infants and assumes that the infant is quite capable of imposing its own order on the incoming stimulus flux. This approach is quite different from that taken by contemporary investigators, who often assume that the infant processes information more competently in isolated bits or chunks than when these bits or chunks are seen in context. Whether or not an "ecological" approach (cf. Gibson, 1979) to infant perception will replace the more popular "feature detecting" approach is unknown; it seems likely that with time and improved tech-

nology the latter approach will gradually incorporate aspects of the former. However, since motion information is present in so many aspects of the infant's visual world, it may be most fruitful to examine the ability to perceive motion in the context in which it naturally occurs, that is, to allow motion to covary with other stimulus features, and examine the interaction parametrically. Such a multivariate approach is a departure from much of infant research but may represent most accurately how the infant perceives and processes information in his/her world.

There has been very little research that has focused specifically on the perception of movement, in which movement covaries with other aspects of the stimulus array. Far more common are those experiments that have incorporated aspects of motion perception, while primarily assessing some other ability. Although such research takes for granted the infant's ability to utilize motion information, a closer look at such research may further elucidate how motion perception plays an integral part in the infant's world. More importantly, such research may help demonstrate how motion perception is really a foundation upon which other abilities build. Thus, the following section will provide a review of those studies of infant behavior that have depended upon the infant's ability to perceive motion but that were actually intended to assess the presence or absence of some other ability.

IV. Indirect Evidence for Motion Perception

1. The Perceptual Constancies

One area of research that has received considerable attention in infancy is the development of the perceptual constancies, specifically object identity and object permanence. There are basically three theories that attempt to explain both constancies.

According to Piaget (1954), an object exists for an infant only as an undifferentiated element of perceptual configurations which are dominated by the infant's action. Thus, an infant tracking a moving object is not really tracking the object per se but is really tracking the locus of perceptual change. Thus, the "thing" that continues to exist when a moving object is occluded by a screen is the action of visual tracking, not the object itself. According to Piaget, object permanence does not develop until approximately 18 months.

A second school of thought is that proposed by Bower (1974). Like Michotte (1962) and J.J. Gibson (1966), Bower claims that object permanence (or "existence constancy") is an innate perceptual constancy. Perceptual processing of information in a stimulus event, such as an object's disappearance, specifies the continued existence of the absent object. Bower, Broughton, and Moore (1971) and Bower and Patterson (1973) demonstrated that infants less than 5 months do not know that when a moving object stops, it remains the same object. This is shown by infants' continuing to track after a moving stimulus has stopped. Bower (1971, 1974) claims that this tracking error is not caused by a

lack of object permanence (as Piaget would have us believe), but rather by a failure of infants to recognize that the moving object is in fact the same object after it stops. Bower says that the confusion about object identity obscures the infant's innate perception of object permanence until 5 months, when this confusion is resolved.

Moore (1975) disagrees with both Bower and Piaget. Moore suggests that the infant's concept of object identity alone (i.e., without object permanence) is sufficient to account for accurate anticipatory tracking of an occluded moving object. According to Moore (1975, 1978), the 5-month-old utilizes two rules of object identity. The first is a spatiotemporal rule which specifies that an object moving from place to place by means of a trajectory is the same object. The second is a feature rule which specifies that an object seen at two successive times is the same object if it has the same features.

Moore, Borton, and Darby (1978) devised three tracking tasks that were designed to distinguish between the three theories by violating one of the concepts hypothesized to be responsible for the 5-month-old's tracking. The authors reasoned that if the infants could be shown to perceive a violation of a particular concept, this would produce evidence that they were using that concept. One condition of each task violated the infant's expectancy for the reappearance of a moving object that disappeared. This was compared to conditions where no violation occurred.

The three tasks included a violation of permanence task, a violation of trajectory task, and a violation of feature task. In the permanence task, a moving object disappeared behind the first of two separated screens and failed to appear between them before emerging

behind the second screen. In the trajectory task, the object reappeared from behind a single screen much faster than would be appropriate, given the object's speed before and after occlusion. In the feature task, an object disappeared behind a single screen, and a featurally different object emerged from the other side of the initial trajectory. All three tasks were administered to groups of 5- and 9-month-olds, along with nonviolation tasks. The authors reported that 5-month-olds showed disruption of visual tracking in the feature and trajectory violation tasks, but not in the permanence tasks. Tracking in the 9-month-olds was disrupted on all three violation tasks. The authors concluded that both 5- and 9-month-olds possess rules specifying the identity of a moving object which is occluded. For 5-month olds, these rules were based on object features and trajectory, but not on the concept of object permanence. All three rules were utilized in the visual tracking of 9-month-olds.

2. Causality

A second and related example of research that has incorporated moving stimuli yet had a primary aim of assessing some other ability has been the research investigating infants' knowledge of causal events.

A key issue in examining causality has been unraveling the extent to which prior motoric experience is necessary before the causal nature between two events can be perceived (e.g., pushing a mobile and observing its movement). Piaget (1952, 1954) claims that the capacity to perceive causality does not begin until after 2 years. Presumably, each time the infant manipulates an object, he/she rediscovers and practices the effect his/her own actions have on that object. Repetition thus

leads the infant to realize that objects may interact in causal ways independent of him/herself. Thus, for Piaget, the development of perceived causality stems from underlying motor experiences the infant has with objects.

An opposing view is that proposed by Michotte (1963) and Gibson (1950, 1966). Both authors argue that causality is perceived directly when certain parameters of constituent events are appropriately defined. Michotte has hypothesized that the perceptual system is equipped at birth to detect causality in certain perceived events. Thus, causality is not based on extensive motor experience but is present in a rudimentary form at birth.

One way to assess the role of prior motor experience is to compare the infant's responses to a perceived event that preserves some of the critical principles of causality to a response to an event that violates this principle. This can be illustrated the following way: If Object A strikes Object B, and B moves off, this preserves a critical principle of causality. On the other hand, if Object A merely moves to Object B and B moves off simultaneously with A's stopping, and there is no contact between A and B, this illustrates a violation of the principles of causality.

Ball (1973) compared 9- to 22-week-old infants' responses to the above tasks after giving them prior exposure to a task in which the central event was occluded by a screen. He found increased attention to the noncontact event over the contact event, suggesting that prior motoric experience with such events was not necessary for perceiving causality.

Borton (1979) gave groups of 3-month-olds both contact and noncontact events, as well as a single object event in which the single object moved horizontally at a constant speed. It was predicted that infants who saw the noncontact event as a violation of the principles of causality would spend a greater proportion of their time looking at the noncontact event vs. the other two conditions. The results supported this prediction. Thus, Borton concluded that 3-month-old infants are able to discriminate between contact and noncontact events, which, although not 'conclusive, is supportive of Michotte's (1963) and J.J. Gibson's (1950, 1966) position.

3. Looming

A final area of interest that has also involved indirect assessment of the infant's ability to perceive motion includes studies examining looming and the infant's knowledge for optical collision.

As the distance between an observer and an object decreases, the angular size of the object grows larger. When the object moves or is thrown at the observer, a flow field is formed within the contours of the object, and thus the projected size of the object increases. If the object will hit the eye, the focus of expansion is within the contours of the object (Rosinski, 1977).

The rate at which changes occur in the flow field and in the projected size indicates the time to collision with an object. These changes occur slowly when the object is far away and increase in rate as it approaches. The projected size increases geometrically with the approach, filling the entire visual field at collision. Rapid expansion of the field indicates collision is eminent. Furthermore, the rate of

expansion specifies the time remaining to collision. Schiff (1965) calls this looming. The motion perspective information involved in looming potentially specifies the approach of the object, whether or not it will hit the observer, and how much time is left before collision.

The ability to use looming information is important for an organism's survival. For example, instances of looming may occur under dangerous situations. Because of its importance, virtually all animals possess the ability to use looming information, often from very young ages. Such is the case with human infants. As will become apparent, however, the conditions under which looming occurs are often not clear.

Hruska and Yonas (1971) showed three groups of infants (1-, 5-, and 9-month-olds) a rear-projected film of an object approaching and receding. Using heart rate as their dependent measure, 1- and 5-month-old infants were found to stare with interest at the approaching and withdrawing object, and showed heart rate deceleration (indicating attention or orientation) to both displays. The older infants also blinked in reaction to the approaching object but not the receding object. At 9 months, there was a marked heart rate acceleration to the approaching object (avoidance response) but a deceleration to the withdrawal.

In contrast to the avoidance response that Hruska and Yonas found only in the older infants, a number of authors have found the same, and often more marked response in much younger infants. Ball and Tronick (1971) exposed infants between 2 and 11 weeks old to two different kinds of looming stimulus displays. Infants were sitting upright in a chair and witnessed either an optical loom (an expanding shadow on a screen) or a real loom (by moving an object directly toward the child). At all

ages and in both situations a pronounced avoidance response occurred; the eyes were opened wide, the head pulled back, the arms were brought up to cover the face, and the body stiffened. When the displays were altered so that the object appeared to go by the infant instead of "hitting" him/her, stiffening failed to occur and the infant turned his/her head and eyes along the path of the shadow or object. The authors reported that the infant's response was reflex-like and it appeared that the infant could easily distinguish between impending collision and a near miss. The same marked avoidance response to impending collision was also found by Bower, Broughton, and Moore (1971) in 2-day-olds.

Ball (1970) suggested that the "head back" response to looming might be due to an attempt by the infant to track the upper contours of the approaching object as it moves upward in the visual field. To test this, Yonas, Bechtold, Frankel, Gordon, McRoberts, Norda, and Sternfels (1977) contrasted the responses of young infants to a rear-projected looming display (a symmetrically expanding contour) with the response to a display in which a contour only moved upward on the screen (thus having no approach information). In 1-month-olds, the symmetrical expansion of contour evoked more upward head movement than a control display, which indicated that the object would miss them by veering sideways. The rising contour evoked even more upward head movement than the symmetrical expansion. By 4 months of age the infants blinked at the end of the collision trial but not at the withdrawal display.

In a comment to the Yonas et al. (1977) paper, Bower (1977) briefly reported the results of a study using a pressure-sensitive transducer placed behind the infant's head. Backward head pressure was measured at

1/2-sec intervals while two types of information were rear projected. Subjects saw a surface rotating downward until almost colliding with the infant's eyes, and a surface rotating upward and away from the face. Once again, Bower reported backward head movements on the downward (collision) trials, but not on the upward trials.

In an attempt to replicate Bower's (1977) results, Yonas and Peterson (1979) used a pressure transducer sampling backward head pressure at 1/2-sec intervals while a real object (foam triangle) was moved toward and away from the infant. No appreciable difference between the two types of displays was evident. The authors felt that the results might still be due to a tendency to track the upper edge of the object as it traveled upward on the approach trials, and to track the contours of the object downward as it withdrew. Furthermore, it may be a sudden darkening of the infant's visual field that evokes backward head movements (i.e., as the object approaches, the visual field is occluded by a lower luminence region). Thus, in a second experiment Yonas and Peterson presented infants with a 6-foot by 6-foot rear-projected screen which alternately lightened and darkened the field of view. These authors reported that darkening the visual field did contribute in part to backward head movement. In yet a third experiment, the authors rear projected two displays: a diamond that expanded symmetrically in all directions or contracted, and a triangle, the top of which remained at line of sight and didn't move upward in the field of view. The results revealed that only the diamond expansion evoked backward head movement. Neither triangle condition elicited any response.

In the fourth and final experiment, a surface was rotated upward and toward the infant until it was 5 cm from the infant's eyes. In a

second condition the object was rotated upward, away from the infant's face. In the "away" condition, 3- to 4-week-old infants tracked the upper contours and moved their heads back. In the collision condition, there was no response except for a gradual lowering of the eye lids as the infant tracked the contour.

In summarizing the research on looming, Yonas and Petersen (1979) comment that there is no evidence that neonates are sensitive to optical information for collision. If blinking is used as an indicator response, then 5- to 6-week-olds may be slightly sensitive to such optical information. It is not until infants are older that the violent upset is found that Ball and Tronick (1971) and Bower (1971) reported.

In summary, the preceding examples have been used to illustrate three areas of infant development that are either dependent upon or inextricably tied to the infant's ability to perceive motion. The development of object identity and permanence, the ability to make causal inferences (about moving objects), and the ability to utilize information for optical collision are all in large part dependent upon the ability to utilize motion cues. Although other aspects of perception are certainly involved, motion cues appear to play a key role and serve as a predominant source of information.

Our world rarely stands still long enough for us to make detailed observations, and the infant's world is no different. Since so much of the world involves movement, it seems not only obvious but even necessary that the ability to perceive movement develop at an early age.

Furthermore, rather than simply serving as an event that is pervasively constant in the development of other abilities, motion perception may actually expedite and enhance the development of a variety of skills. For example, the fact that infants consistently prefer the same stimulus when it is moving as opposed to stationary suggests that motion enhances the saliency of a given stimulus. The fact that newborn sucking suppression fails to habituate to a moving stimulus but not to a stationary one suggests that moving stimuli in general are more appealing to infants. Moving stimuli appear intrinsically more salient than nonmoving ones, which suggests that movement perception is somehow "special" relative to other visual functions. Its function may take two forms. First, it may serve as a stimulus attractant that permits particular competencies to develop. Thus, one might speculate that the development of the perceptual constancies and causality, as well as the ability to utilize information for optical collision, would all be delayed if not inhibited completely without the ability to perceive motion and the special nature of motion to maintain attention. Second, motion perception may facilitate discrimination of stimuli and even aid in the development of other abilities. For example, Wilcox and Clayton (1968) and Carpenter (1974) found increased attention to moving vs. stationary faces. If, as Haith has suggested, infants habituate more slowly to moving vs. stationary objects, and if this pattern also holds for animate objects, this may suggest that moving attributes of faces (e.g., moving mouth, blinking eyes, bobbing head, etc.), because of their increased saliency, are more of an aid to the recognition and discrimination of faces and parts of faces than are the static attributes. As a consequence, recognition of faces and facial expression may also be aided by the infant's

ability to utilize movement cues.

Because of the abundance of movement in the infant's world, it is indeed curious that static stimuli are employed as much as they are in research examining the infant's visual abilities. At one level this is understandable; the addition of movement would merely contribute unwanted variance in many experiments. However, there have been a great number of questions asked of infants where the addition of movement would be useful. For example, where infants are being asked to discriminate faces, invariance of pose, and facial expression, the addition of movement (e.g., a moving mouth and/or a bobbing head; cf. Haith, Bergman, & Moore, 1977) might not only serve to maintain attention but also increase "external" or "ecological" validity. The same might also be said of some studies examining concept formation, cross-modal perception, and even learning. For example, if movement carries additional stimulus information--which might account for its preferred status over stationary stimuli (cf. Neisser, 1976)--would learning be enhanced in some infants if moving vs. static stimuli were employed? The point is that it would be to our benefit to take advantage of one component of the infant's world that not only exists in great abundance but that also has some "specialness" about it and that infants are able to utilize from an early age.

The major point addressed by this section has been that movement plays a key role in infant perception. Although the relevant literature has been reviewed and some suggestions have been made for future research, what has been deleted is a discussion of why movement is important and how the observed differences between moving and stationary stimuli can be explained. More precisely, how can one theoretically ex-

plain the infant's perception of movement and account for its place in infant development? This is no easy task, as the lack of theory in explaining movement perception is even greater than the lack of research. In the following and concluding section is a review of several theories of movement perception and an evaluation of each in terms of its ability to explain the infant's perception of movement. Finally, a model of infant motion perception will be proposed, and suggestions will be made regarding the direction of future research and how such research will contribute to a model of infant motion perception.

V. Theories of Motion Perception

A substantial portion of this paper was devoted to a review of neural mechanisms sensitive to motion information. The major conclusion drawn from this work was that these mechanisms are probably not fully functional in newborns, but may reach maturity by 3 to 4 months of age. However, despite the existence of such mechanisms, the role they play in perception is unclear. Certainly the simplest way of accounting for the perception of movement would be to propose that successive changes in the environment stimulate adjacent retinal points. A model of this sort would then only need a "code" to detect these changes. Such codes might be mapped onto the visual system anatomically (such as the velocity and direction-specific cells reviewed earlier), physiologically (e.g., Hebb's cell assemblies or Pribram's neural junctions), or "hypothetically" (e.g., frequency filter or feature models). Although the coding model is attractive, it nevertheless appears beset with

problems.

First, the physiological research in the area has been conducted with nonhumans, and has employed exceedingly simple stimuli, such as lines and gratings. Stimuli of this same nature also make up the data base in much of the human psychophysical research. Thus, it is unclear whether or not motion detection at a neural level exists only for lower-order stimulus arrangements, and whether or not there is a code for all manner of stimuli. Second, for a model of motion detection to be robust enough to account for all or many forms of movement, one must be able to show how a perceiver differentiates successive stimulation of adjacent retinal loci caused by object motion as distinct from motion of the eyes or body (i.e., both forms of movement produce displacements of retinal projection), yet we rarely attribute our motion to that of the visual world. Finally, like feature-detection models, a model of motion detection is atomistic and assumes that the component parts of the motion array can be neurally reassembled to recreate the observed motion. Such additive-elements thinking can be fallacious. An analogy might be useful: Anderson (1977; cited in Thoman, 1978) claims that while the elements of a crystal can be separated and identified, the converse is impossible; that is, it is impossible from a knowledge of the particles of a crystal to predict its symmetry. Thus, the perception of a moving stimulus may be far more complex than the sum of all the motion-sensitive cells indicating movement.

In summary, although neural motion detectors undoubtedly play some role in the perception of movement, such models at present scarcely account for the everyday perception of moving stimuli. Although the model is attractive, more research needs to be done before one could

consider such an approach sufficient to account for everyday perception, especially infant perception.

A second model of motion perception is that proposed by James Gibson (e.g., 1959, 1966, 1969, 1976, 1979). According to Gibson, the motion of objects with respect to other objects is perceived when the retinal projection contains a perspective transformation associated with kinetic optic occlusion. As an object moves, it progressively covers and uncovers the texture of the surface behind it. Gibson describes the consequence of this change in retinal projection as a "wiping out" of the texture at the leading border, an "unwiping" at the trailing border, and a "shearing" of texture at the lateral border (Haber & Hershenson, 1973; Gibson, 1966). The perspective transformation is associated with a break in continuity of the texture of the background. This kinetic occlusion specifies the existence of an edge, of depth at the edge, and of one surface behind another. Thus, an object in motion produces a transformation in its own perspective projection on the retinal surface and relative changes with respect to its texture and that of the background.

More recently, Gibson (1979) has specified three varieties of events that are distinguished in movement perception. These include changes of surface layouts (translations and rotations of an object, collisions, deformations, and disruptions), changes of surface color or texture (e.g., "nameless" but significant alterations of surfaces of plants and animals), and changes in the existence of structure (transitions of evaporation, dissipation, melting, dissolving, and decay). Gibson is adamant in stating that the optic array contains all the in-

formation necessary to perceive movement. He further states that one should not speak of motions per se in the array, but rather of disturbances. It is the direct perception of these disturbances that gives rise to the perception of movement.

Gibson's theory is appealing because the perception of motion relies solely on identifiable optic information. The model is far more robust than the motion detection model in accounting for how motion perception occurs, largely because of its ability to specify the optic parameters that guide perception. Nevertheless, objections to the theory have been raised on two grounds: First, Gibson has failed to specify how the pickup of information indicating "disturbances" in the optic array is accomplished. For example, what makes it possible to accept information of a particular type, and what function does the pickup of a particular type of information play in directing further explorations aimed at acquiring still more information (Neisser, 1976)? Second, Gibson's theory tends to ignore evidence in neuropsychology and experimental psychology which suggests that perception may be a process from the inside out as well as the outside in. For example, Gyr (1972) has reviewed research suggesting that information about the voluntary motion of the eye and its relation to reafferent input is important in perception (e.g., Von Holst, 1954; Festinger, Burnham, Ono, & Bamber, 1967). This notion runs counter to Gibson's, as it emphasizes the importance of extraoptic, central parameters in perception, which Gibson considers as unimportant. Examination of this third model might be helpful.

In its original version, the visual-motor integration theory (Helmholtz, 1866) attempted to solve the problem of differentiating observer from object motion by postulating that changes in feedback information from the eye or body position were subtracted from changes in retinal displacement. For example, if there was a displacement of projection on the retina of 10 degrees to the right, but also feedback from the eye muscles that the eye had made a 10 degree movement to the left, the two bits of information would cancel and no movement would be perceived.

In reviewing the evidence presumably in support of Helmholtz's theory, Spiegel (1965) claimed that the position sense of the eye was not precise enough to provide input for the type of computation proposed by Helmholtz. Furthermore, since the latency to initiate saccadic eye movements is approximately 200 ms, feedback from actual changes in eye position would be too slow.

In 1954, Von Holst modified Helmholtz's theory by replacing feedback from eye position with feedback from the efferent or outgoing signals of the brain which control eye, head, and body movements. Von Holst proposed that if the normal animal moves, for example, to the left in a stationary environment, an efferent copy of left movement as well as the visual reafferent signals associated with such movement are compared in the CNS. In this example, the two signals are of opposite sign, and thus cancel one another, indicating to the animal that no change took place. However, if the same afferent optic input is not accompanied by an efferent copy (as when the environment moves but the animal doesn't), the meaning to the animal of the afferent input is changed, thus leading to tracking behavior to the right to follow the motion of the environment. From this point of view it would appear that

animals record relations between themselves and their environment.

Other investigators have offered corroborating evidence for Von Holst's theory (e.g., Sperry, 1950; Von Holst & Mittelstaedt, 1950; Paillard & Brouchon, 1966; Rock, 1966; Teuber, 1960), thus providing mounting evidence that under some circumstances, the perception of motion includes a comparison or correlation between the efferent commands to muscles with the resulting visual afferent consequences--a perceptual-motor integration. Gyr (1972) has postulated that one way this integration might be achieved would be for the brain to store a copy of the commands for movements at the time it sends them out. When input from the receptors reaches the brain, it would automatically be compared to the stored copy. If it matches, the input is then taken as feedback (reafference), so the effect of retinal displacement is attributed to eye movements. If it doesn't match, then the input is interpreted as the consequences of independent external events, which gives rise to the perception of movement. Thus, unlike Gibson's theory, the perceptual-motor theory suggests that nonoptic information is also necessary for the perception of movement to take place.

Although the visual-motor integration model is intuitively appealing, its present usefulness in accounting for the infant's perception of motion is limited. At the moment, the only means available for testing notions of reafference and exafference lie with elaborate surgical techniques, stabilized retinal images, or adapting prisms, all of which are impossible or difficult to use with infants. (A recent study by McDonnell and Abraham [1979] did successively use adapting prisms with young infants, although their interests were not in addressing the visual-motor integration model.) This is unfortunate, as the theory is

quite competent in accounting for many forms of the adult's perception of movement. Present technology appears to be the limiting factor in testing the model with infants. However, there is a second problem with the theory, which is its failure to state when such afferent-efferent correlations are necessary to perceive movement. In other words, under what circumstances, and how frequently, are extraoptic parameters necessary to perceive movement? Only after testing the theory with humans in conditions that approximate everyday perceptual activities will this question be satisfactorily answered. As ever, further research is necessary.

The theories reviewed above differ in the emphasis they place on cortical-mediated perception. Motion detection theory relies solely on cortical "units" sensitive to motion information, while Von Holst's theory emphasizes an integration of environmental and cortical events. For J.J. Gibson, perception does not occur in the brain per se, but rather in the retino-neuromuscular system as an activity of the system (1969). In fact, perception is a circular process, with retinal inputs leading to, for example, ocular adjustments, which in turn lead to altered retinal inputs, with the process then repeating. Because the three theories assign different roles to the brain in mediating perception, the nature of the stimulus events that give rise to the perception of motion also differ. The motion-detection and visual-motor integration models are nonspecific in this respect, while Gibson's model specifies these events exactly. The emphasis placed on identifying the stimulus instead of the process is one feature which makes Gibson's

model testable with infants. This feature may not make it more correct, but it does make it more open to empirical validation. Unfortunately, such validation has yet to occur.

VI. Future Directions for Research

In this paper an attempt has been made to address three aspects of the infant's perception of movement. First, what do we specifically know about this ability? Second, what implications might this ability have for later development? Third, how can movement perception be explained within some theoretical framework? To achieve this goal, we began by describing the remarkable sensory capacity infants possess at birth, and suggested that this capacity is sufficiently advanced to provide the infant with the ability to perceive movement from an early age. Next, the work of those investigators who have specifically examined the infant's ability to perceive movement was reviewed. It was argued that infants from birth are able to track moving objects. They also show attentional preferences for moving vs. stationary objects and, in addition, respond differently to different types of movement. This discussion was followed by a review of three aspects of infant development which are dependent upon the ability to perceive movement, yet have not been studied as such. It was concluded that without this ability, these and possibly other aspects of development might be delayed or inhibited. Thus, the perception of movement appears "special" relative to other visual behaviors. In an attempt to explain why

this ability might be special, and how this ability might develop, three contemporary theories of movement perception were reviewed. A question remains, however, as to whether these theories can provide insight into describing how the infant perceives movement.

Any effort to explain the infant's perception of movement must consider in part what we know of this ability in the adult; after all, the adult's abilities represent the culmination of the full development of the infant's abilities. What may distinguish the infant from the adult he or she will become is that the adult has more or less incorporated the ability to perceive motion into his/her complex everyday behavioral repertoire while the infant probably has not. Movement, per se, is one of many stimulus features determining adult attention. For infants, movement appears to be a disproportionately salient feature. Three facets of the infant literature seem to support the preeminence of movement for infants. First, infants show attentional preferences for moving vs. stationary objects, suggesting that there may be higher order information in the former which supercedes attention to the latter. Second, infants respond differently (i.e., habituate at different rates) to different types of movement, suggesting that the information available in a stimulus may govern attention, and that this information may vary within the class of moving objects. Finally, infants respond differently to the same type of movement at different ages; looming is a good example of this. These bits of evidence appear to collectively substantiate the notion that the processes underlying movement perception are different from those underlying the perception of static stimuli, and that the integration of these processes may be one charac-

teristic of development. If our goal is to describe this process and explain how infants' abilities eventually take on adult-like characteristics, then we have much to gain by understanding how the adult perceives movement. The problem confronting the infant researcher, however, is deciding which of the theories reviewed earlier accounts best for the infant's perception of movement. This problem is actually threefold. First, which theory will best account for the existing infant data? Second, which theory can be modified to take into consideration the limited abilities of our species' young? Finally, which theory can actually be tested with infants?

As mentioned earlier, the easiest way of accounting for the infant's perception of movement would be simply to interpret the existing infant data from the perspective of an adult model. In light of both the data and our current state of methodological sophistication, the "coding" or neural detection model seems least applicable: Not only would it be difficult to develop a "code" to fit the data, but it would also be difficult to verify the data once they were accumulated, short of conducting histologies on infants of varying ages. Secondly, although Von Holst's theory is intriguing, it, too, would be difficult to validate. More importantly, it may be superfluous in explaining the existing data. For example, a simple description of the optical parameters of a stimulus might be sufficient to explain why one stimulus is preferred over another or why some stimuli take longer to habituate to than others. Extra-optic parameters may simply be unnecessary. Naturally, this assumption would need to be tested, but, as already mentioned, such tests would be difficult to conduct.

Gibson's theory is attractive for two reasons. First, it appears that some of the existing data might be explained by providing a description of those events which compose the optic array. Second, the emphasis placed on the stimulus makes it empirically attractive and relatively easy to test. However, there seem to be aspects of the data which are not easily accounted for by the theory. For example, why are infants able to track a toy train entering a tunnel, and then correctly anticipate its reappearance? If such behavior cannot be accounted for solely by the ecological optics of the situation (which remain to be "seen"), then we must rely on "extra" optic parameters, such as internal mediation brought about as the result of repeated observations of the phenomenon. Nevertheless, Gibson's theory might be an excellent starting point from which to develop a model of infant motion perception. With the appropriate modifications to fit both the data and the abilities of our young organism, such an attempt seems quite feasible. The question that must now be addressed is what kind of model could be constructed that would provide fruitful directions for research.

Perhaps the most interesting feature of the infant motion perception literature is that infants respond differently to moving vs. stationary objects. This is reflected most importantly by noting the slower rate of habituation to moving vs. stationary objects, and that the rate of habituation itself actually varies within the class of moving stimuli. These results were earlier interpreted to mean that movement carries additional information that stationary stimuli fail to carry, and that this information may actually vary depending on the type of movement. As a result, movement is somehow "special" in the infant's

world. Why this is so is not clear, but a piecemeal interpretation of the literature might suggest something along the following lines.

Moving stimuli frequently contain information that stationary objects lack. For example, if a ball is passing vertically in front of an infant, there may be a change in texture gradient, repeated occlusion and disocclusion around the edges of the falling object, and added cues to depth. In Gibson's terms, it is the direct perception of the "ecological optics" of this situation that facilitates the perception of movement. In addition, these same optics carry information other than the perception of the ball moving, and information that is not afforded by stationary objects. Keeping with the ball example, not only is information about the ball being acquired, but so is information about the surround. The relationship between the ball and its surround must be noted, especially the area that first preceded and then later fell behind the ball's path. The context of the ball's falling should thus be far more salient than if the ball were stationary. That is, attending to changes in the ball's position must also require attending to changes in the surround, such as the repeated appearance and disappearance of an edge. In all, a moving object appears salient because it conveys information not only about itself but also about its context. As a result, there are a variety of stimulus events that occur simultaneously and successively, which is not the case with stationary objects. In the end, the perception of movement provides more information about more parameters than the perception of a static array, assuming all other stimulus features are held constant.

If moving objects in fact contain information over and above that afforded by stationary objects, how, then, is this information picked up? It has already been noted that infants habituate slower to moving objects than to stationary objects. It seems reasonable to assume that rate of habituation is at least in part dependent upon the extent to which the infant is attending to the stimulus. A reasonable explanation of why moving objects sustain relatively more attention than stationary objects is that the "disturbances" in a moving array preserve an element of novelty about the stimulus through its continuous change. As Haith has suggested, infants observing a moving stimulus expect a certain degree of change. While stationary objects manifest no such change, the degree of change within the class of moving objects actually varies depending on the type of movement. If the object movement is predictable, then the infant's expectations are met, and he/she habituates to the stimulus. However, if the object movement is unpredictable, these expectations are violated and habituation occurs at a much slower rate (thus sustaining the infant's attention).. Different types of movement, therefore, possess different degrees of novelty, in that some are more predictable than others. For example, infants in Gibson et al.'s (1978) study habituated fastest to looming motion, which consisted of a simple front-back movement. If rate is kept constant--which it was--then infants should have little trouble in predicting what the stimulus will do next, and thus the stimulus eventually becomes increasingly familiar. Taken to its logical conclusion, what maintains attention is progressive change, unpredictability, and continual novelty.

In summary, moving objects are intrinsically more interesting than their stationary counterparts because they preserve an element of novelty. Once the infant's attention has been successfully recruited, attending to the details of the optic array serves to facilitate the pick-up of important information. This additional information may further enhance the object's novelty, which, in addition to the extent to which the movement is unpredictable, may account for why different types of movement are responded to differently (i.e., different types of movement vary in the information they impart), and how predictable they are. In all, movement may aid and/or facilitate information acquisition because it sustains attention and because it carries additional information.

In order to complete the above logic, we need to specify why a particular type of information is acquired. Furthermore, we need to specify what function the pickup of a particular type of information plays in directing further explorations aimed at acquiring still more information. If habituation represents a form of learning, then infants who habituate to a particular type of movement and dishabituate to a second type have learned something about both forms of movement. How this learning contributes to the pickup of new information is not clear, but several alternatives seem likely. At a cortical level, neural assemblies which store this information might be formed. Later these assemblies serve as a template against which other forms of information can be compared. "Information acquisition routines" (cf. Mendelson & Haith, 1976) might then consist of the continual storage, retrieval, and comparison of motion information picked up from the optic array.

Neisser (1976) offers a second alternative to the problem. Neisser feels that the cognitive structures crucial for vision are the anticipatory "schemata" that prepare the perceiver to accept certain kinds of information rather than others and thus control the activity of looking. A "schema" is defined by Neisser as: "that portion of the entire perceptual cycle which is internal to the perceiver, modifiable by experience, and somehow specific to what is being perceived. The schema accepts information as it becomes available at sensory surfaces and is changed by that information; it directs movements and exploratory activities that make more information available, by which it is further modified" (p. 54). Like the notion of cell assemblies, the notion of schemata would also be sufficient to account for how information pickup leads to further information pickup. Unfortunately, there are no known cortical correlates for a schema concept, so its possible physical principles remain elusive.

At present, the most likely explanation for the infant's perception of movement is that the novel nature of a moving stimulus captures the infant's attention. Once the infant attends to the stimulus, the additional information afforded by the moving array is available for pick-up and acquisition. It might further be speculated that the information acquired by attending to the optic array is somehow "incorporated" into the infant's existing visual behavior repertoire, and such information may influence subsequent information pick-up. Information pick-up eventually becomes a repeating, self-perpetuating process.

Research efforts to evaluate the above hypothesis may take three directions. First, it would be advantageous to systematically explore

the psychophysical parameters of moving stimuli. It would be of particular importance, for example, to explore infants' thresholds to varying rates of movement and how infants discriminate subtle differences in types of movement and to systematically vary the optical parameters that give rise to the perception of movement.

A second research effort would be devoted to examining the interface between type of movement and type of stimulus. As mentioned earlier, there may be developmental differences in how different types of movement interact with different types of stimuli. For example, a face oscillating around a horizontal axis should be perceived with greater interest at 6 months than a top rotating around the same axis. Definitive statements concerning the perception of movement would be greatly aided by examining such interactions.

Finally, an invaluable line of inquiry might be devoted to developing a paradigm that makes it possible to systematically vary different stimulus components yet incorporate these components into an "environmentally valid" context. The aim of such an effort would be to explore the perception of movement when movement covaries with other stimulus events that might occur naturally. Such an approach would be quite conducive to examining individual differences in selective attention, and, by simulating conditions which approximate those confronting the infant in his/her everyday life, pave the way for a new study of infant perception.

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